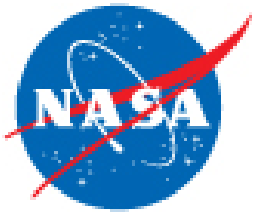
National Aeronautics and
Space Administration



Metrics for V&V of Cyber defenses

Martin S. Feather, Joel M. Wilf, Joseph Priest

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Acknowledgements

JPL's Cyber Defense Research Initiative

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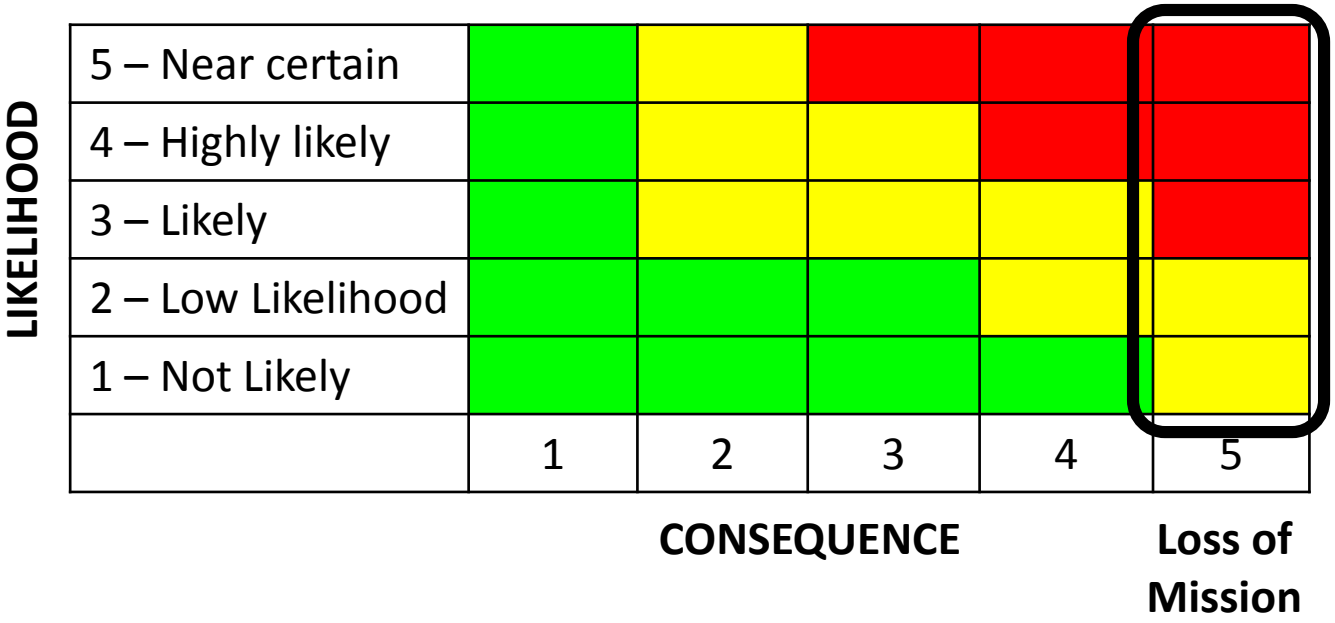
- DJ Byrne
- Chris Dorros
- Ed Silber
- David Foor

Motivation for cyber defense

ASSUMPTION:

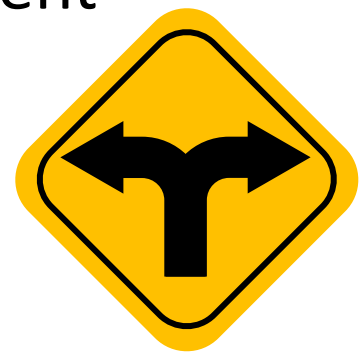
you already agree that
cyber threats** are a **serious risk



Likelihood hard to estimate but there are known to have been cyber penetrations of space assets

Problem

- Context: Contemplating introducing a cyber defense into a flight project environment (development or operations)
- Question: *should it be deployed?*
- Approach to answering:
  - Adaptation of a traditional V&V workflow
  - Collection & presentation of appropriate metrics
  - Help inform deployment decision



Context for this work

JPL's Cyber Defense Research Laboratory

GOAL: "To develop, evaluate and validate cyber defensive architectures and mitigations for JPL missions in a controlled environment and in the presence of attacks"

FEATURE: a sandboxed computing environment in which security tests and experiments can be run without risk of damage to production systems

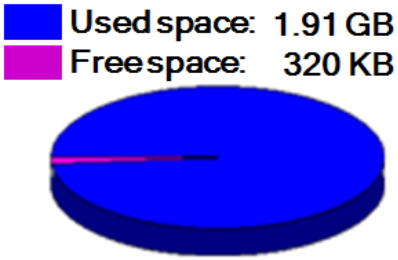
Cyber defense concerns

- Costs
- Benefits
- Risks

Take all these into account
when gauging its acceptability – trade-offs involved

Cyber defense concerns - Costs

- Budgetary
  - Purchases and license fees
  - Labor costs
    - Installing and maintaining the defense
    - Operating the defense (e.g., helpdesk, sysadmin)
    - Trainer and trainee costs of mastering the defense
- Computational
  - CPU, memory, filespace, bandwidth (acceptability will depend on unused capacity)
- User Inconvenience
  - Extra user steps
  - Decreased usability / curtailed capabilities
  - Interruptions/interference (e.g., from false positives)



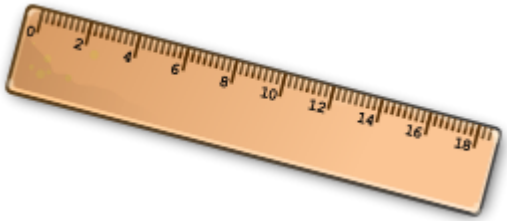
Cyber defense concerns - Benefits

- Nature of defense
  - Prevention – inhibits steps of cyber attack(s)
  - Detection (and the kind of response it leads to)
  - Recovery – assists in recovering after a cyberattack
  - ❖Logging for forensics later
- Additional security (if any)
  - While designed for one kind of attack, helps against others
- Efficacy
  - Sensitivity & specificity
    - Don't miss attacks ("false negatives")
    - Don't generate false alarms ("false positives")
  - Responsiveness (limits the time/extent of attack)
- Additional benefits (if any)
  - E.g., cleanup leading to less downtime, faster normal processing

Cyber defense concerns – Risks

- Vulnerabilities
  - New or increased “attack surface”
  - Impede or undermine other defenses
- Critical interference
  - Under some circumstances (e.g., off-nominal): minor inconvenience escalates to major impediment

Assessment



Field candidate defense in operational environment and measure its costs, benefits and risks?

NO!!!!!!!!!!!!!

Assessment

Field candidate defense in "sandboxed" test environment and measure its costs, benefits and risks?

YES!

- Safe – isolated from institutional network so malware cannot escape
- Non-disruptive to ongoing operations
- Repeatable experimentation

Unhappy gremlin added to
http://www.nasa.gov/mission_pages/apollo/40th/jsc_lunar_sample_lab_30.html

Fidelity of test environment

"Test like you fly, fly like you test"

- Many "confounders" of test fidelity
  - Fewer computational resources (CPUs, routers, …)
  - Fewer users and applications; lack of true usage profiles
  - Short-lived duration of tests
  - Subset of full computational milieu
    - Networks
    - Firewalls
    - Other security controls
  - Virtualization perhaps not reflective of operational environment

http://en.wikipedia.org/wiki/File:VictorVPhonograph.jpg |Description = Victor V Disc Phonograph (Gramophone) |Source = Collection of John Lampert |Date = 2006 |Author = Norman Bruderhofer |Permission = Creative Commons Share Alike 2.5

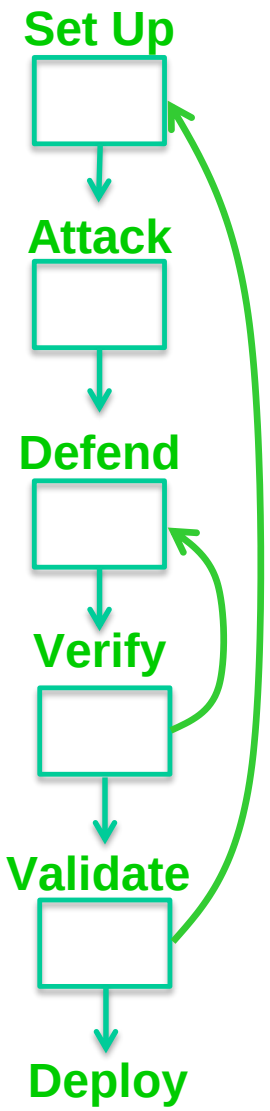
Analogy with space testing

> *"The lunar environment cannot be sufficiently emulated on Earth, therefore system verification testing will rely to some extent on extension by analysis and ultimate testing in the field (lunar operations)."*
>
> [P. Craven, N. Ramachandran, J. Vaughn, T. Schneider & M. Nehls. "Test Before You Fly – High Fidelity Planetary Environment Simulation", Global Space Exploration Conference (GLEX), 2012.]

- Experiment in test environment to take measures
- Analyze & extrapolate to operational environment
- If confident, deploy to operational environment
  - Maybe test there
  - Probationary period
  - Subsequent monitoring

V&V workflow

- Set Up: configure test environment
- Attack: take measurements as cyber-attack is conducted in test environment
- Defend: develop & deploy defense in test environment, take measurements during no attack, and during attack
- Verify: with real users, extrapolate measurements to infer effects in operational environment; assess acceptability
- Validate: Carefully (and reversibly!) field in operational environment
- Deploy: commit defense to use

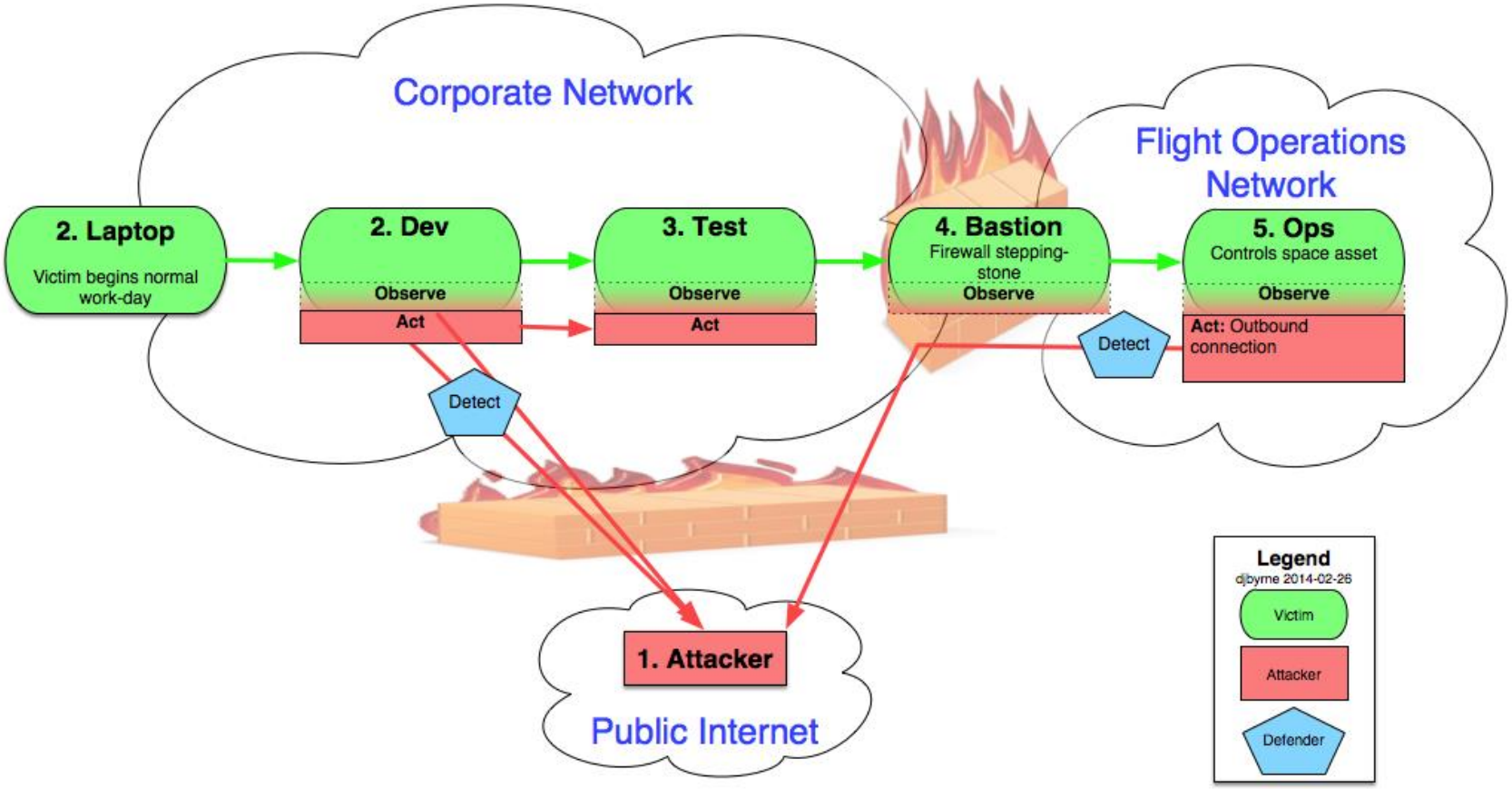


A RUNNING EXAMPLE MAY HELP…

Image courtesy of Ambro at FreeDigitalPhotos.net

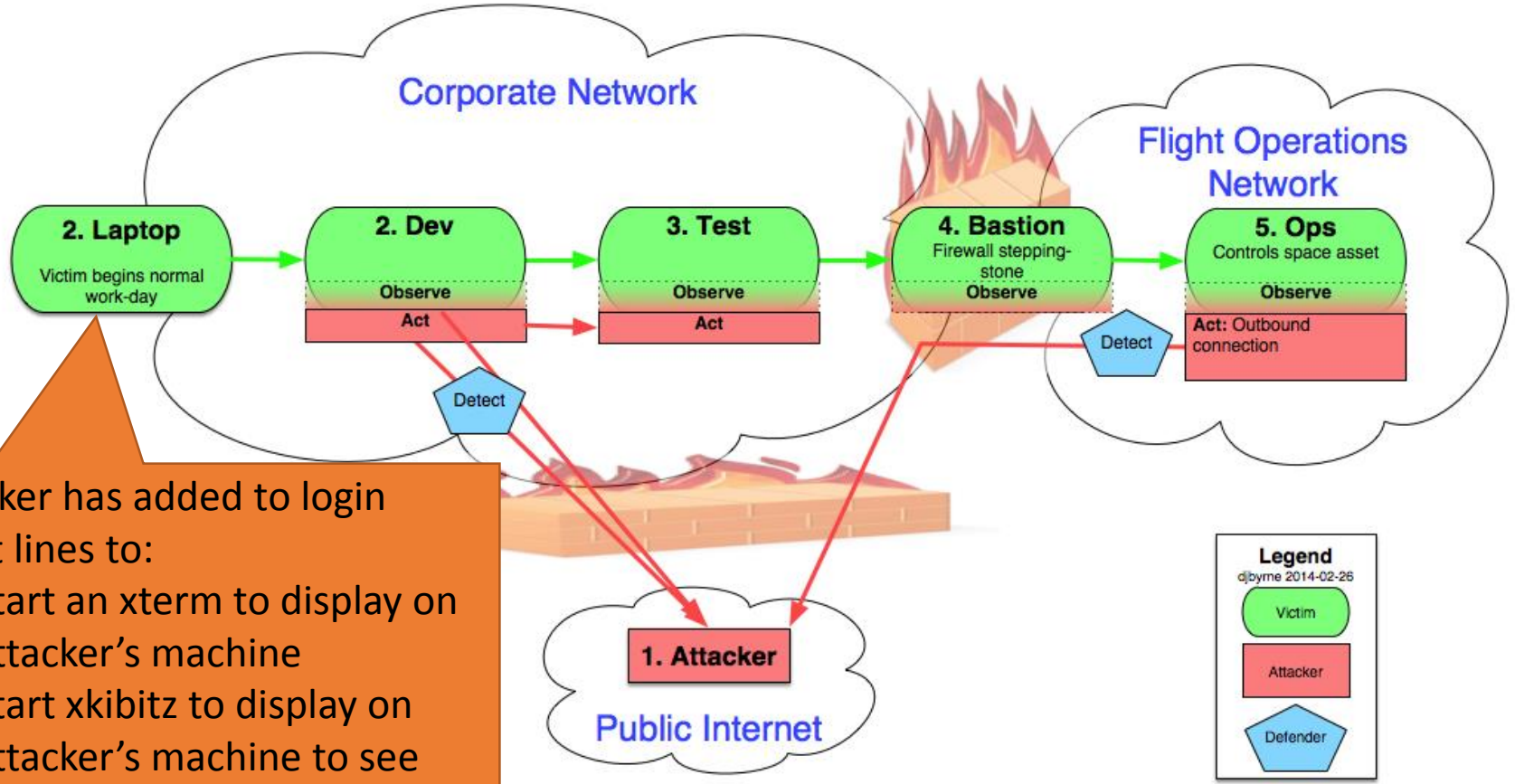
“Reconnaissance attack”

D.J. Byrne, D. Morgan, K. Tan, B. Johnson and C. Dorros, *“Cyber Defense of Space-Based Assets: Verifying and Validating Defensive Designs and Implementations”*, Conference on Systems Engineering Research (CSER 2014) Procedia Computer Science, 28 (2014), 522-530



"Reconnaissance attack"

Initial breach: attacker has had brief access to victim's home directory (multiple plausible ways this could occur)

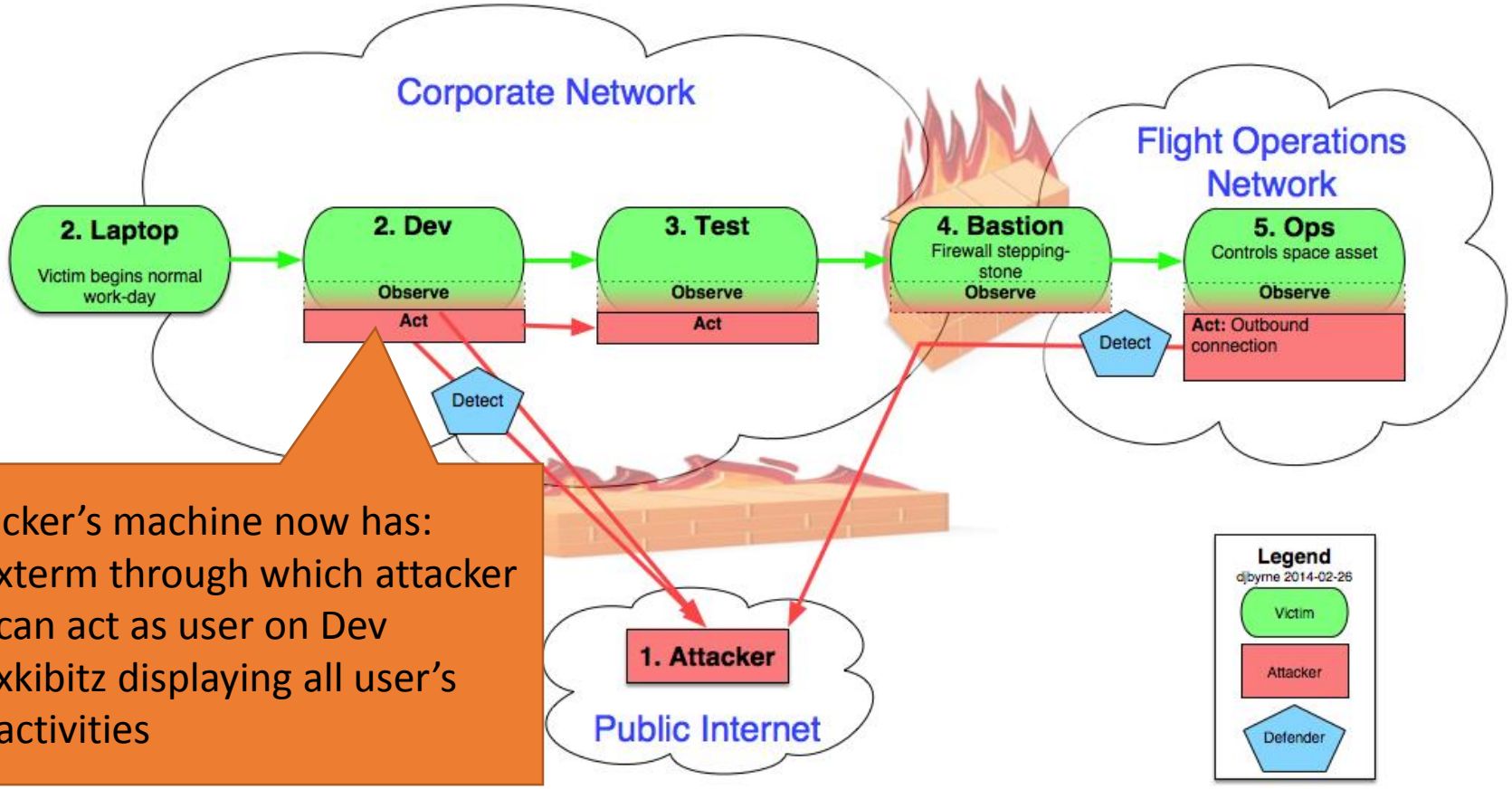


Attacker has added to login script lines to:

a. Start an xterm to display on attacker's machine
b. Start xkibitz to display on attacker's machine to see everything victim does

"Reconnaissance attack"

Victim logs in to Dev using multi-factor authentication

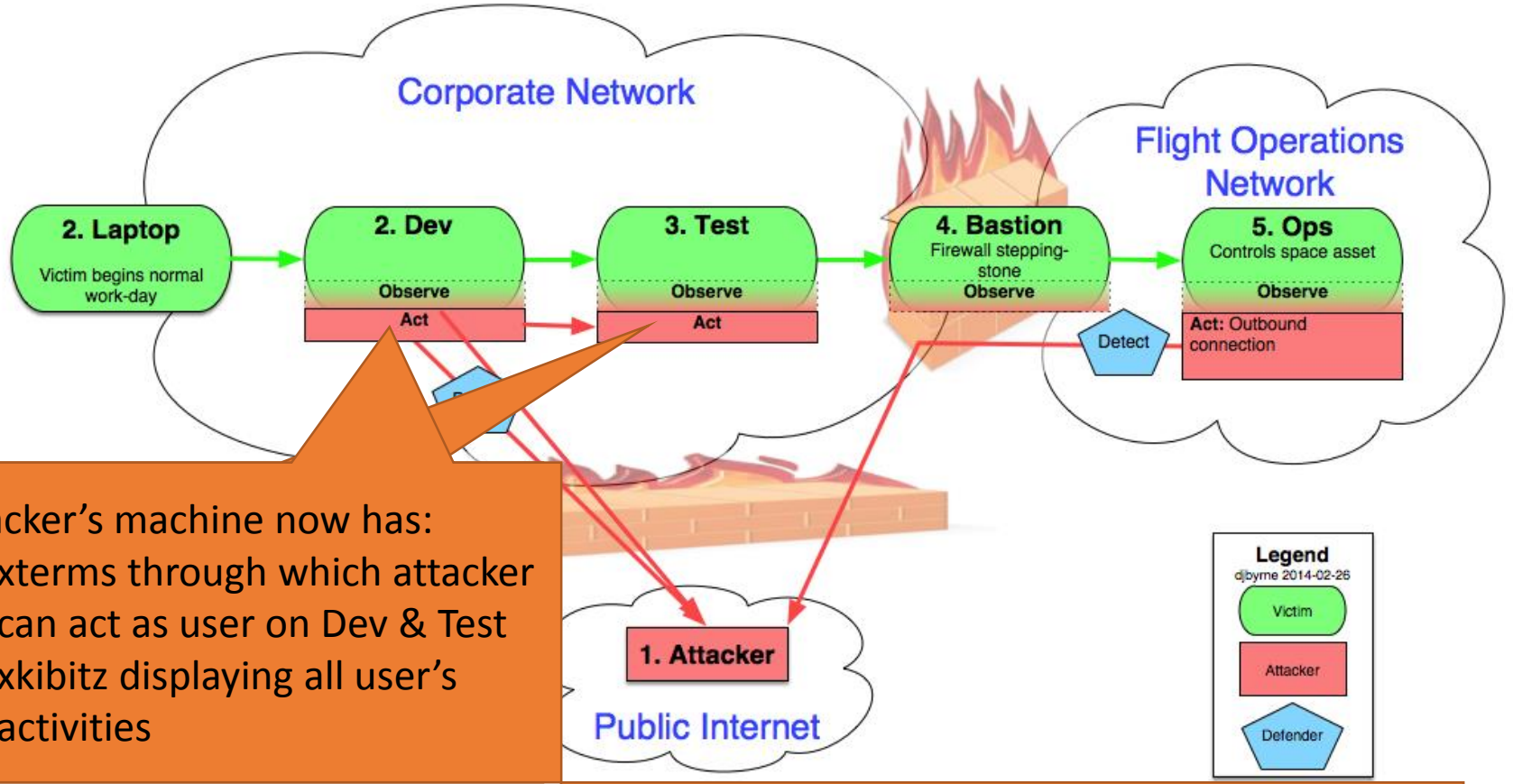


Attacker's machine now has:

a. xterm through which attacker can act as user on Dev
b. xkibitz displaying all user's activities

“Reconnaissance attack”

Victim logs in from Dev to Test using “Single Sign On” ticket



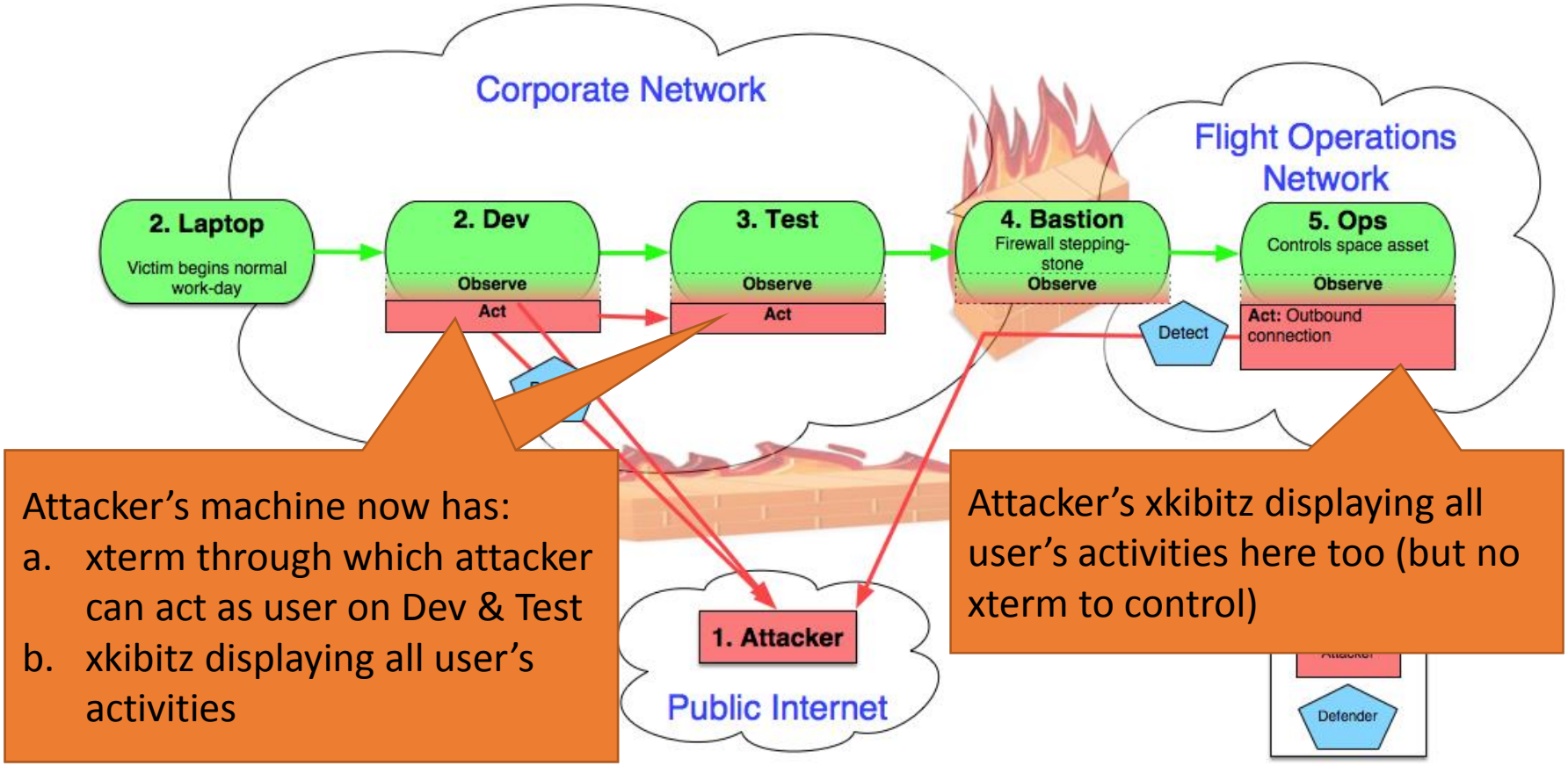
Attacker’s machine now has:

a. xterms through which attacker can act as user on Dev & Test
b. xkibitz displaying all user’s activities

Note: xterms persist after victim has logged off!

"Reconnaissance attack"

Victim logs in through Bastion to Ops (requiring multi-factor authentication again)



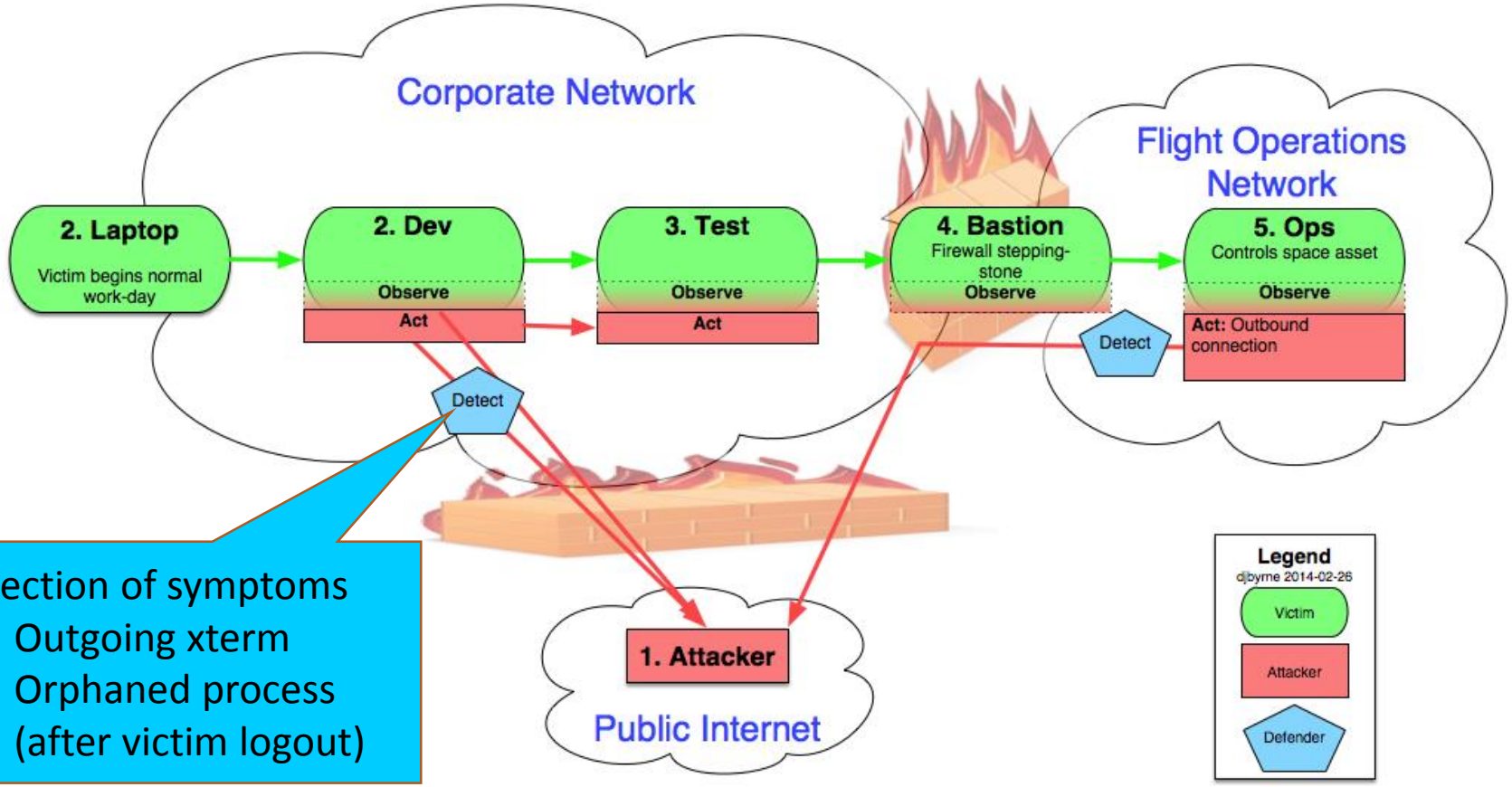
Attacker's machine now has:

a. xterm through which attacker can act as user on Dev & Test
b. xkibitz displaying all user's activities

Attacker's xkibitz displaying all user's activities here too (but no xterm to control)

"Reconnaissance attack"

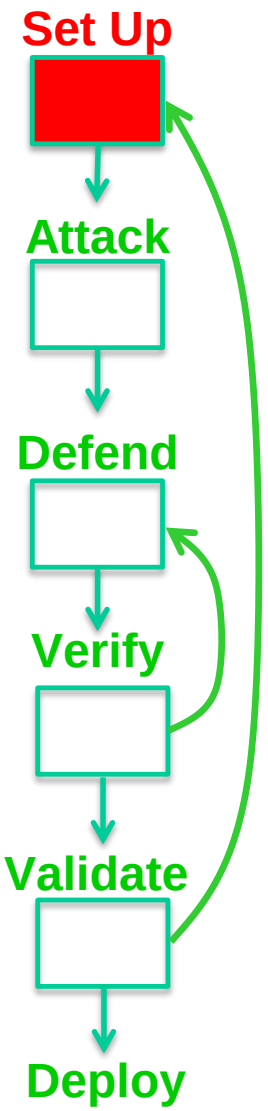
Victim logs out, goes home for the day



Detection of symptoms
i. Outgoing xterm
ii. Orphaned process (after victim logout)

V&V workflow – Set Up

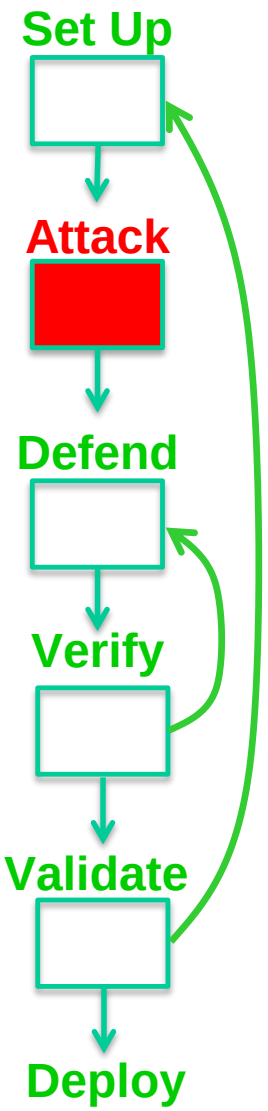
- Identify system and scenario(s) to be defended
  - Spacecraft commanding – confidentiality & integrity
- Select or design cyber attack to be defended against
  - "Reconnaissance attack"
- Determine (test?) that the cyber attack would be a threat in the *operational* environment
  - Possible to test; observed in the wild; plausible
- Configure test environment to model operational environment as required
  - High fidelity like environment in CDRL (Lab) (CPUs, Network, authentication services, …)
  - WE SIMPLIFIED FURTHER
  - *Virtualized* CDRL setup (absent irrelevant services…)



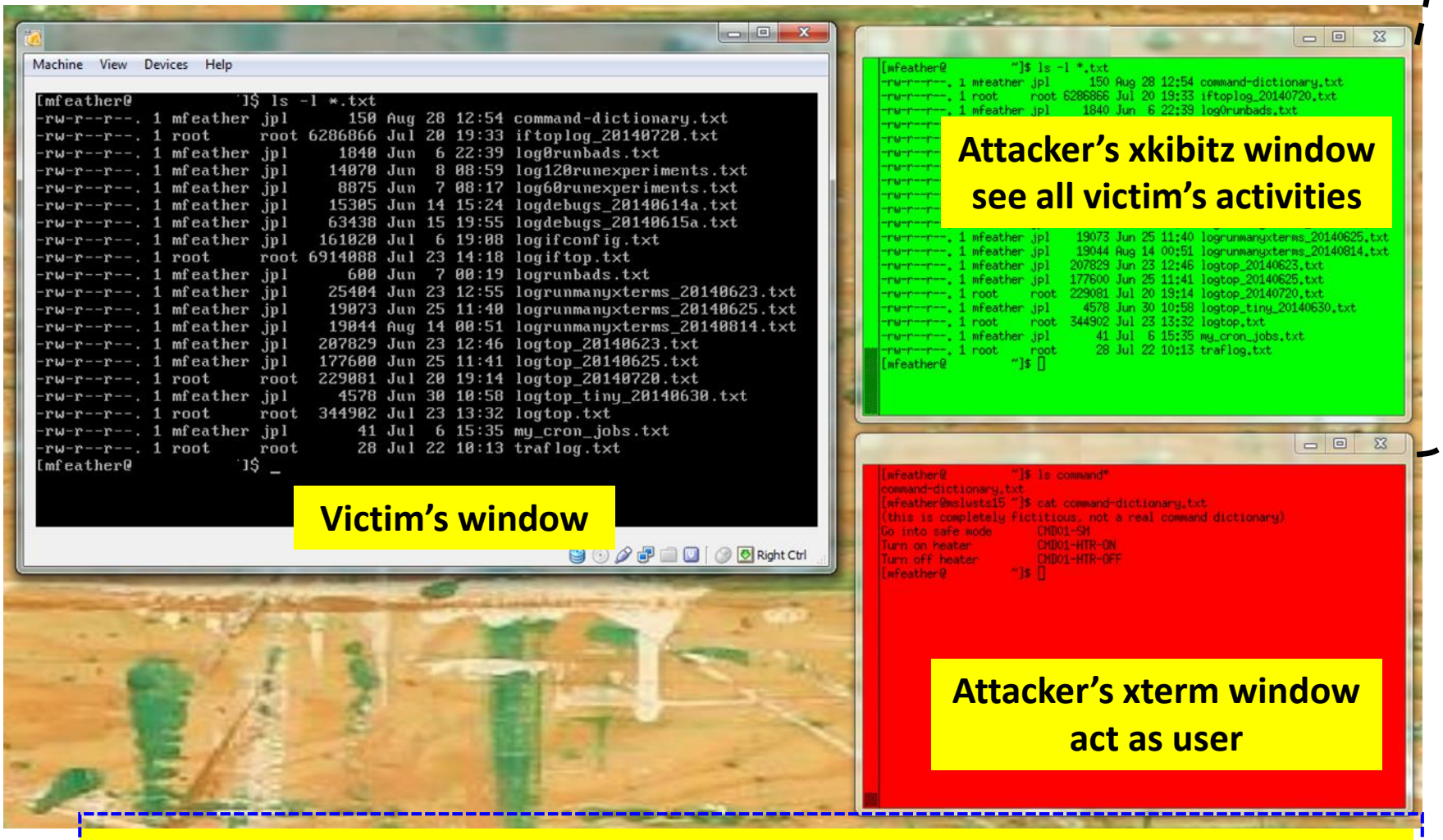
V&V workflow – Attack

- Determine that the attack succeeds
  - In *test* environment
  - Without the defense present

  Yes, when victim logs in, xterm & xkibitz open on attacker's machine ✓
- Measure attack effects – breaches of:
  - Confidentiality – view victim activities ✓
  - Integrity – perform user-allowed actions, persists even after victim logs out ✓
  - Availability – ignored (but also plausible)

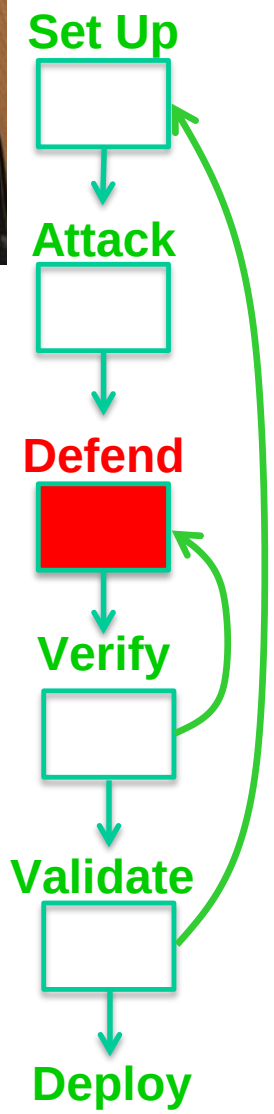


V&V workflow – Attack



Screenshot of laptop running reconnaissance attack in virtual test environment

V&V workflow – Defend



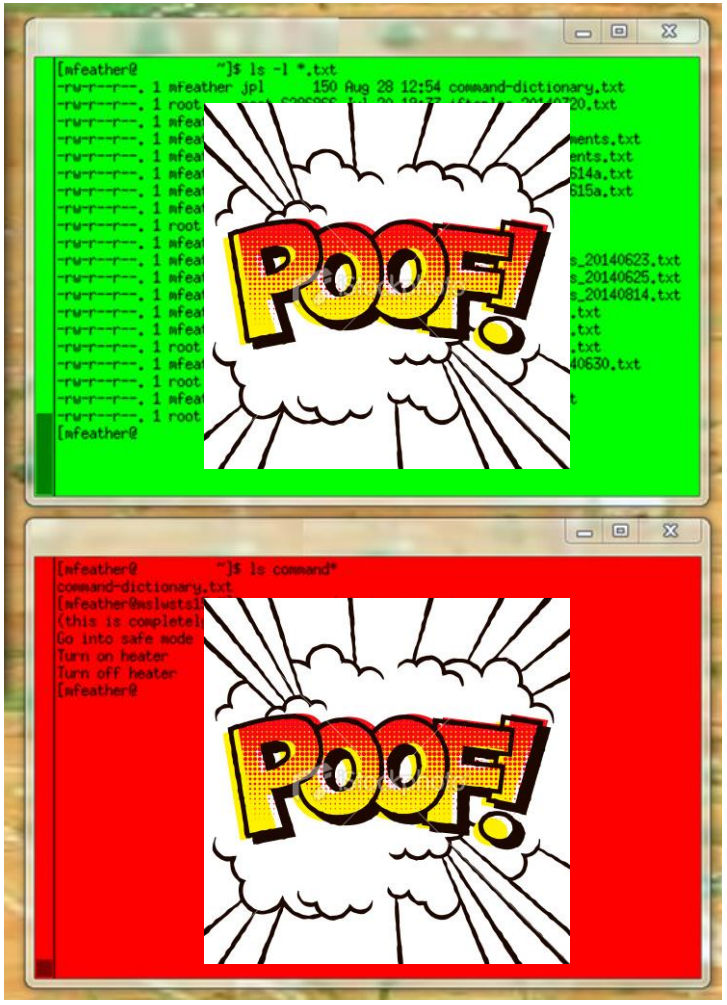
- Develop defense, deploy in *test* environment
  Commercial network monitoring + query for detecting remote xterm + *automated* response to kill rogue process on victim's machine
- Take measurements during *no* attack
  - Understand the computational etc. costs of the defense, its interference on normal operation, etc.
    CPU, memory, network; license & monitoring host $
- Take measurements during attack
  - Efficacy of the defense at preventing / detecting & responding to / recovering from the attack
    durations of attacker's xterm & xkibitz windows

V&V workflow – Defend

Automated response

```
[mfeather@          ~]$ ls -l *.txt
-rw-r--r--. 1 mfeather jpl      150 Aug 28 12:54 command-dictionary.txt
-rw-r--r--. 1 root     root 6286866 Jul 20 19:33 iftoplog_20140720.txt
-rw-r--r--. 1 mfeather jpl     1840 Jun  6 22:39 log0runbads.txt
-rw-r--r--. 1 mfeather jpl    14070 Jun  8 08:59 log120runexperiments.txt
-rw-r--r--. 1 mfeather jpl     8875 Jun  7 08:17 log60runexperiments.txt
-rw-r--r--. 1 mfeather jpl    15305 Jun 14 15:24 logdebugs_20140614a.txt
-rw-r--r--. 1 mfeather jpl    63438 Jun 15 19:55 logdebugs_20140615a.txt
-rw-r--r--. 1 mfeather jpl   161020 Jul  6 19:08 logifconfig.txt
-rw-r--r--. 1 root     root 6914088 Jul 23 14:18 logiftop.txt
-rw-r--r--. 1 mfeather jpl      600 Jun  7 00:19 logrunbads.txt
-rw-r--r--. 1 mfeather jpl    25404 Jun 23 12:55 logrunmanyxterms_20140623.txt
-rw-r--r--. 1 mfeather jpl    19073 Jun 25 11:40 logrunmanyxterms_20140625.txt
-rw-r--r--. 1 mfeather jpl    19044 Aug 14 00:51 logrunmanyxterms_20140814.txt
-rw-r--r--. 1 mfeather jpl   207829 Jun 23 12:46 logtop_20140623.txt
-rw-r--r--. 1 mfeather jpl   177600 Jun 25 11:41 logtop_20140625.txt
-rw-r--r--. 1 root     root  229081 Jul 20 19:14 logtop_20140720.txt
-rw-r--r--. 1 mfeather jpl     4578 Jun 30 10:58 logtop_tiny_20140630.txt
-rw-r--r--. 1 root     root  344902 Jul 23 13:32 logtop.txt
-rw-r--r--. 1 mfeather jpl       41 Jul  6 15:35 my_cron_jobs.txt
-rw-r--r--. 1 root     root      28 Jul 22 10:13 traflog.txt
[mfeather@          ~]$
```

```
[mfeather@          ~]$ ls command*
command-dictionary.txt
[mfeather@nslwsts15 ~]$ cat command-dictionary.txt
(this is completely fictitious, not a real command dictionary)
Go into safe mode       CMD01-SM
Turn on heater          CMD01-HTR-ON
Turn off heater         CMD01-HTR-OFF
[mfeather@          ~]$
```



V&V workflow – Verify

- Verify:
  - Cyber experts converse *with real users*
  - Extrapolate measurements from *test* environment to infer effects in *operational* environment
    Note: beware of confounders to test fidelity

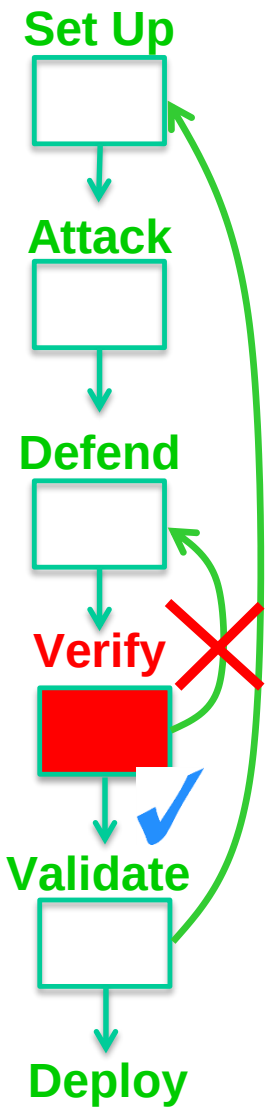
Are extrapolated results acceptable?

✓ YES: advance to Validate

(to determine acceptability in *operational* environment)

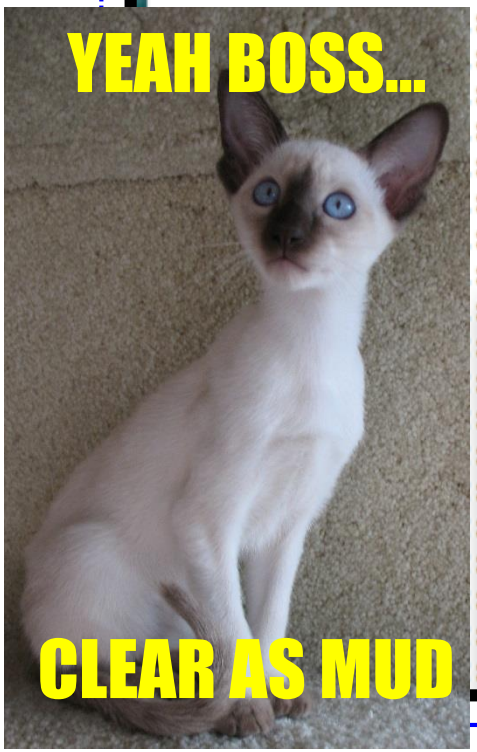
✗ NO: return to Defend

(to address identified improvement needs)



V&V workflow – Verify

- Verify:
  - Cyber experts converse *with real users*



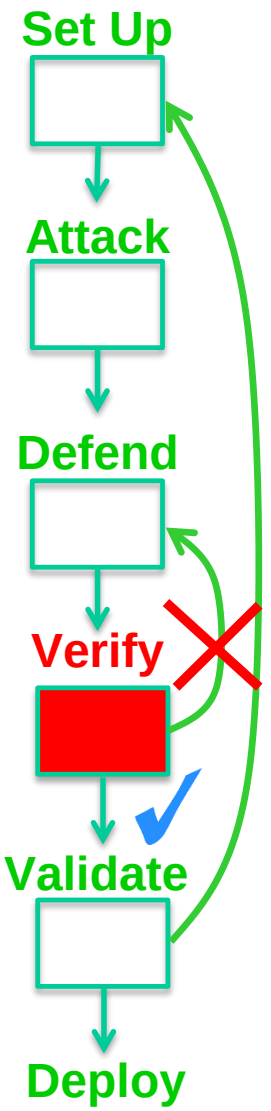
2014-07-23 12:41:09 0
2014-07-23 12:41:14 0
:19 0
:24 0
:29 0
:34 1.25
:39 1.3
:44 0.58
:49 0.48
:54 0

2014-07-23 12:40:57 0.76 0.005
2014-07-23 12:40:59 0.76 0.055
2014-07-23 12:41:01 0.70 0.01
2014-07-23 12:41:03 0.70 0.01
2014-07-23 12:41:05 0.70 0.049
2014-07-23 12:41:07 0.80 0.039
2014-07-23 12:41:09 0.80 0.059
2014-07-23 12:41:11 0.74 0.015
2014-07-23 12:41:13 0.74 0.025

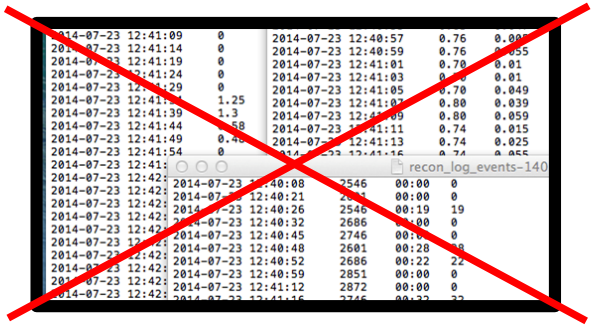
recon_log_events-140

2014-07-23 12:40:08 2546 00:00 0
2014-07-23 12:40:21 2601 00:00 0
2014-07-23 12:40:26 2546 00:19 19
2014-07-23 12:40:32 2686 00:00 0
2014-07-23 12:40:45 2746 00:00 0
2014-07-23 12:40:48 2601 00:28 28
2014-07-23 12:40:
2014-07-23 12:40:
2014-07-23 12:41:

Reconnaissance attack's raw measurements captured in log files

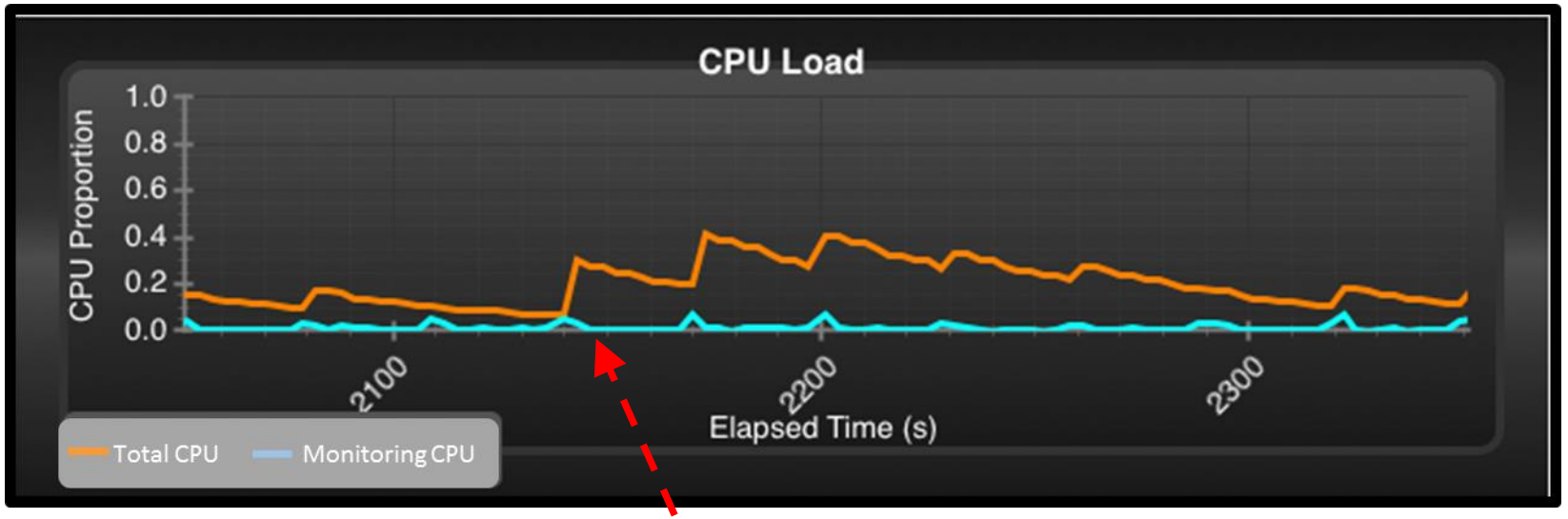


Information Visualization



Total load on CPU

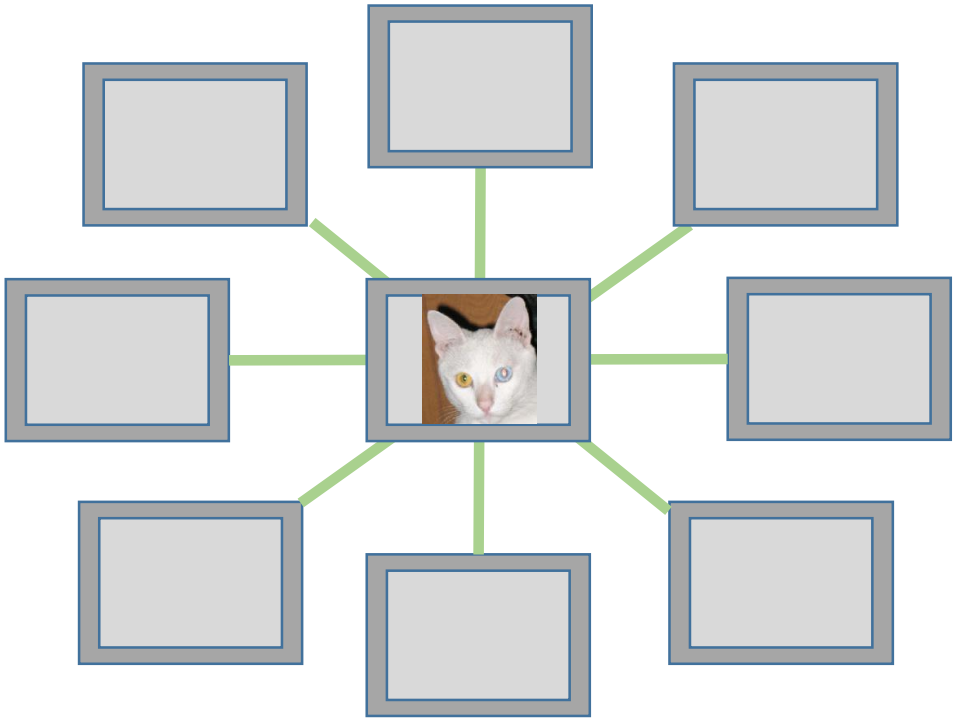
Monitoring's load on CPU



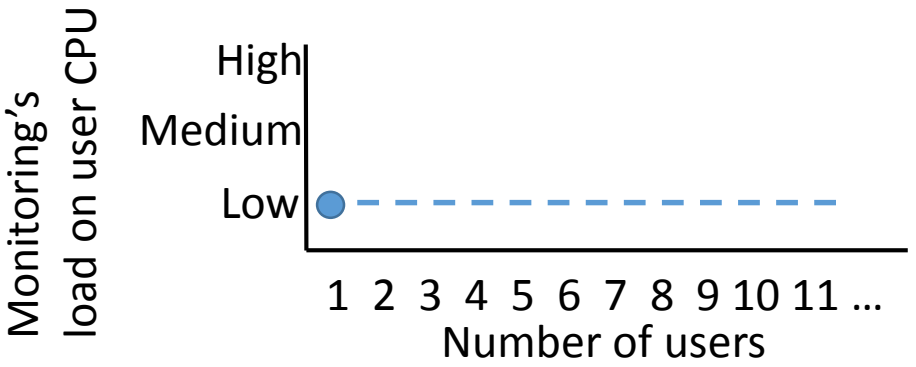
Monitoring's CPU load on user's machine *low* relative to system load & capacity

Extrapolation

Monitoring architecture: information from users' machines sent to dedicated machine for analysis & detection

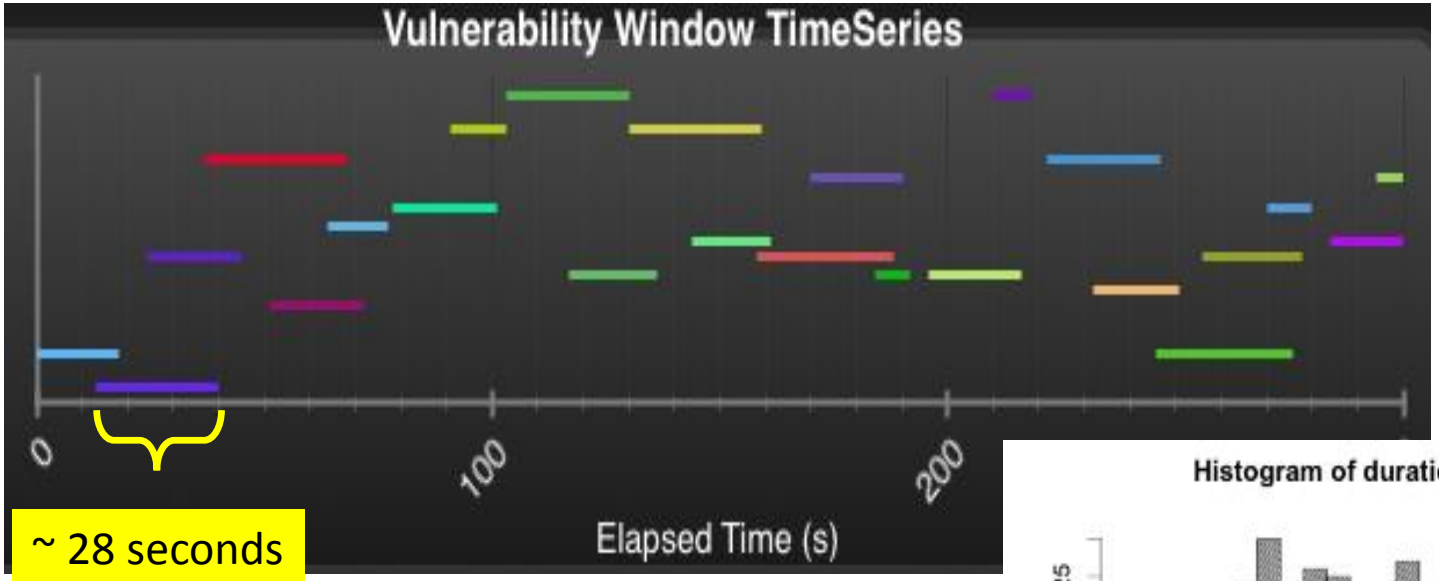


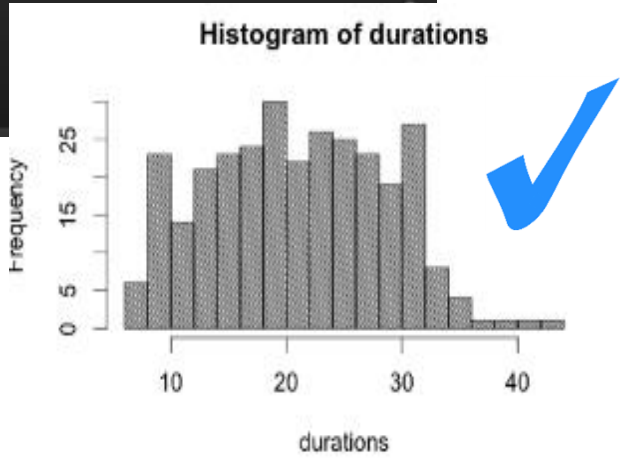
Monitoring's CPU load on user's machine independent of number of user machines – remains low



V&V workflow – Verify benefits

Colored line segment = duration of vulnerability (attacker's xterm or xkibitz window open)

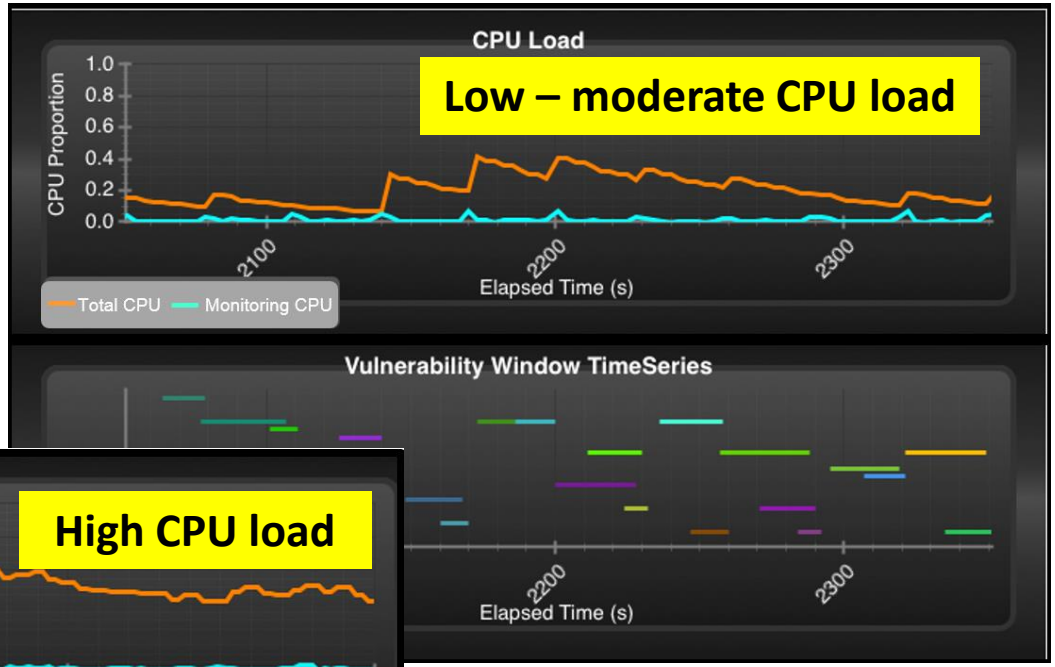


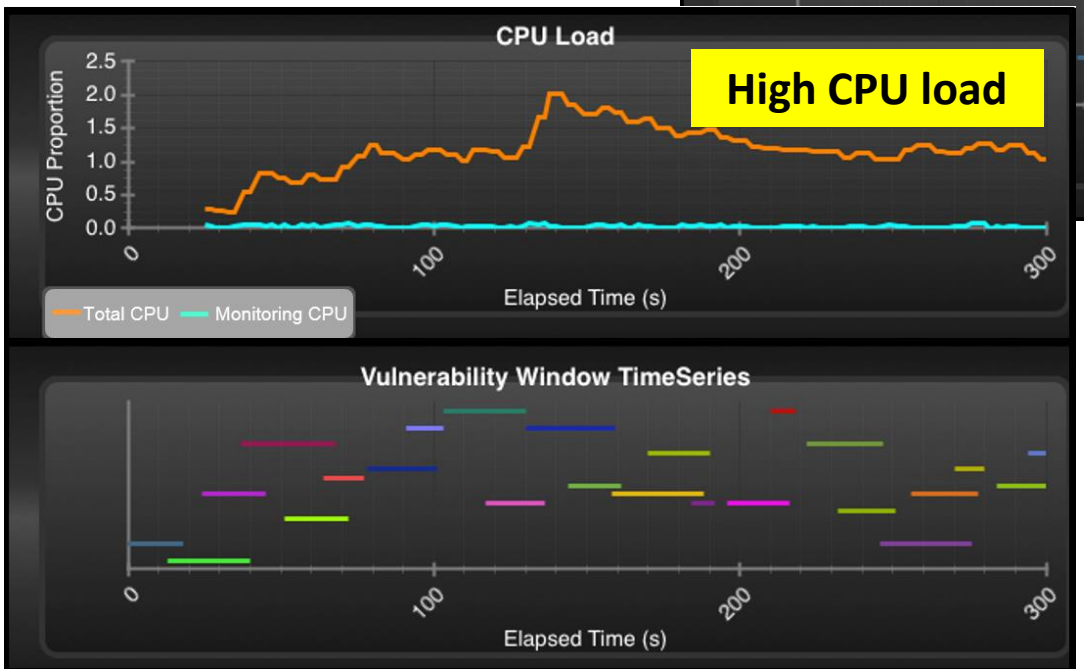


Reconnaissance attack repeatedly initiated to speedily gather lots of data

V&V workflow – Verify benefits

Experiments conducted in different CPU load conditions

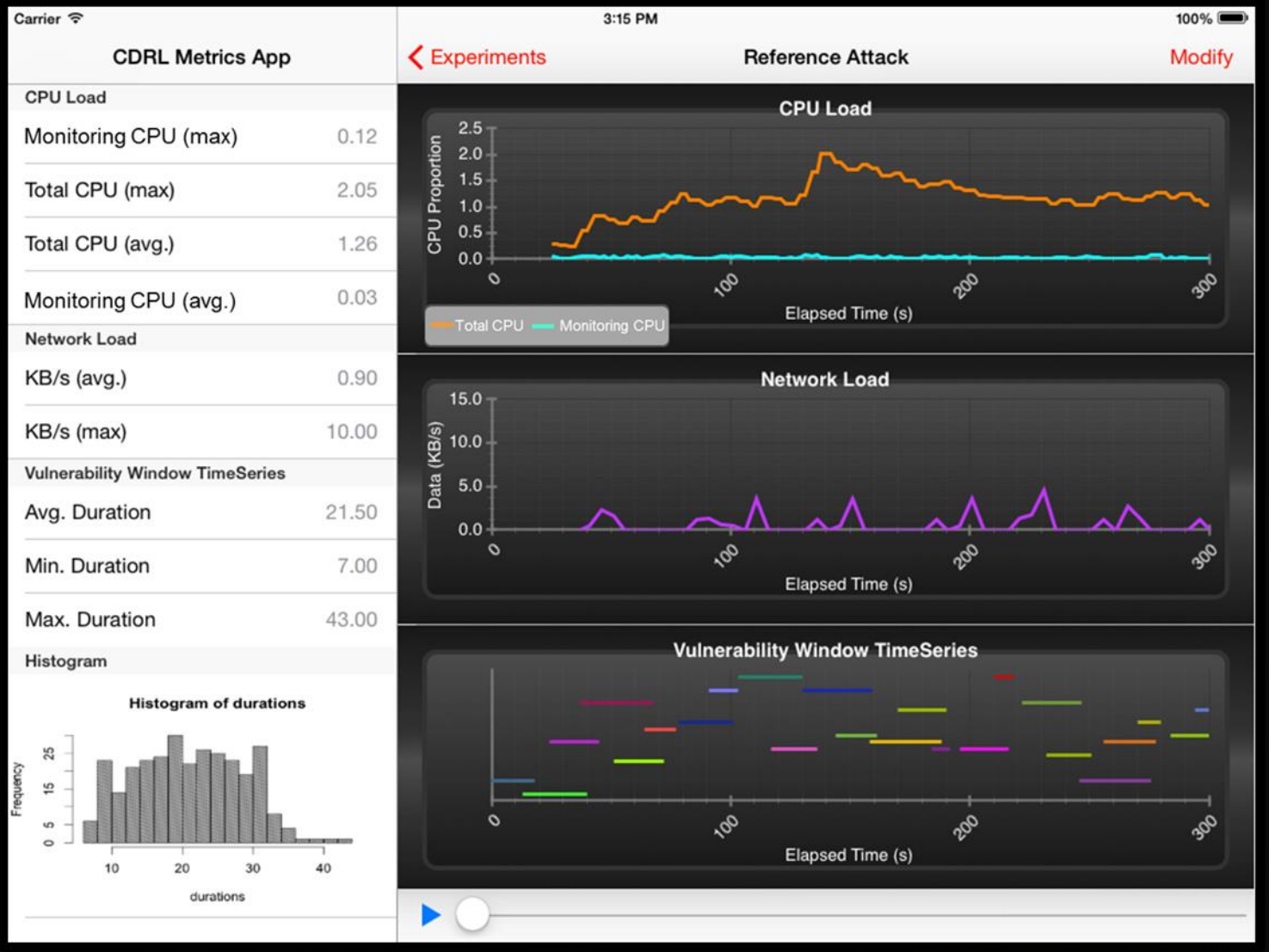




Vulnerability durations only slightly increased (~1 sec)

Metrics dashboard

Mobile metrics dashboard



Intended for iPad display

V&V workflow – Verify costs

Commercial network monitoring
+
Dedicated machine for its analysis & detection

Justifiable if can amortize over other monitoring needs

Cannot keep open *any* remote xterm

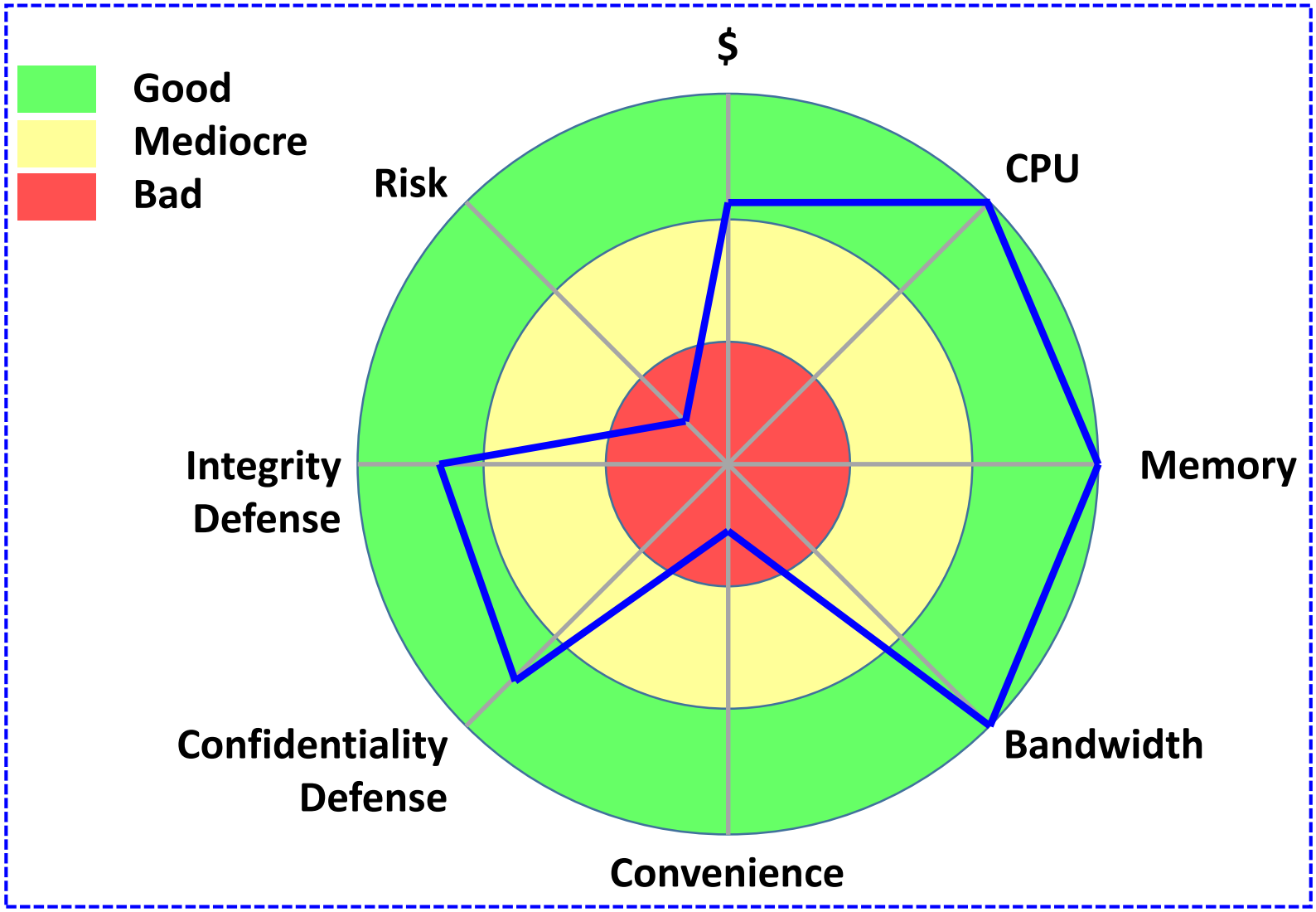
Unacceptable user inconvenience

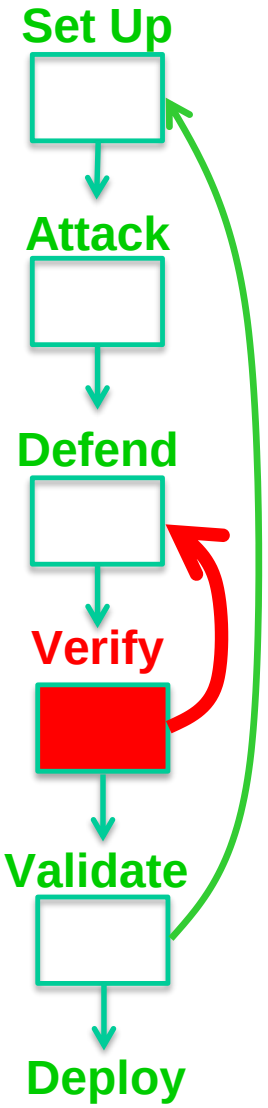
V&V workflow – Verify risks

Passwordless-ssh as mechanism to kill rogue process

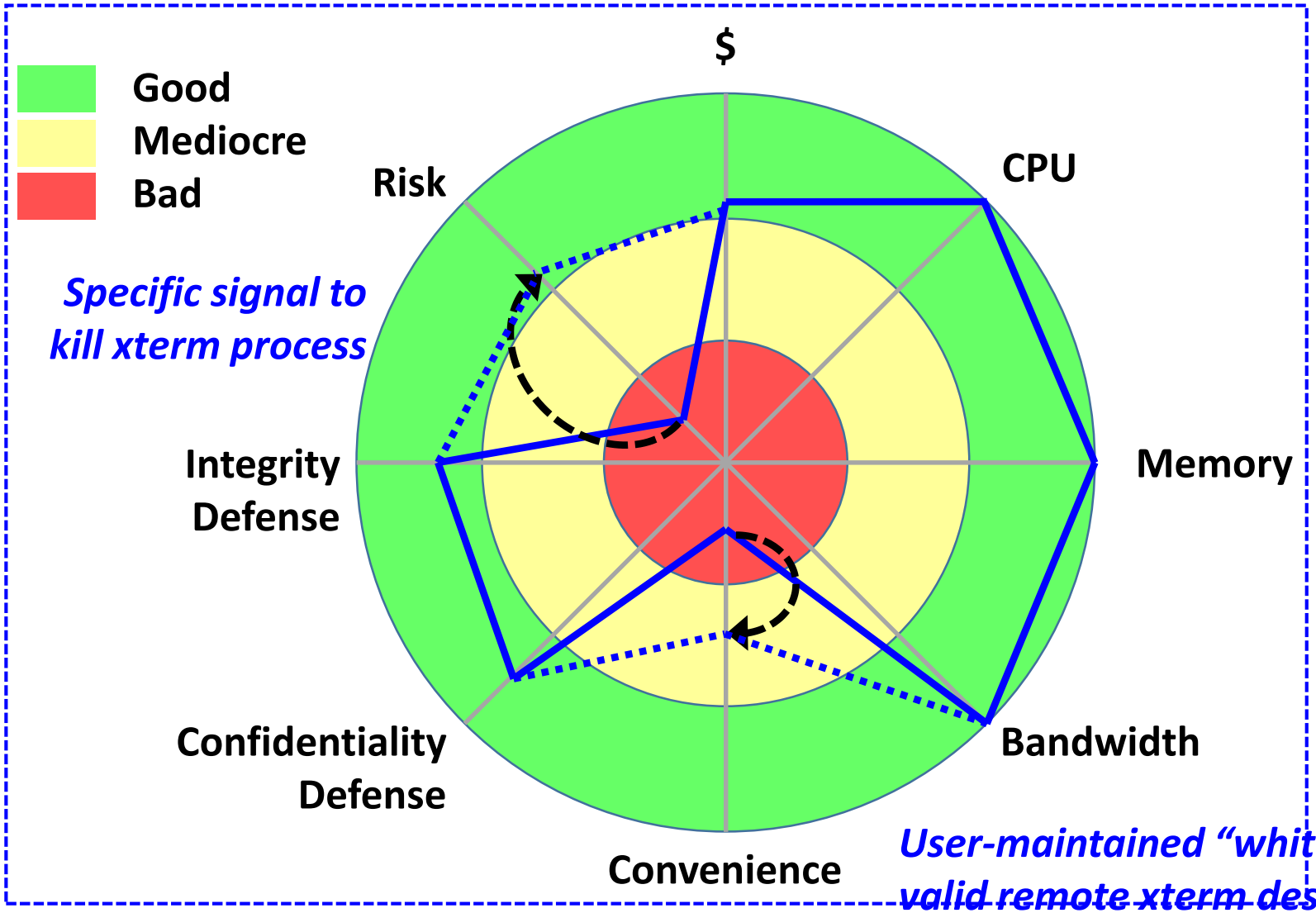
Violates principle of least privilege

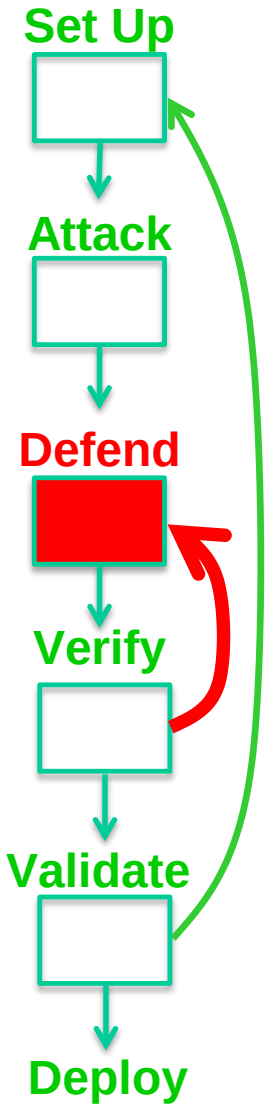
V&V workflow – Verify status



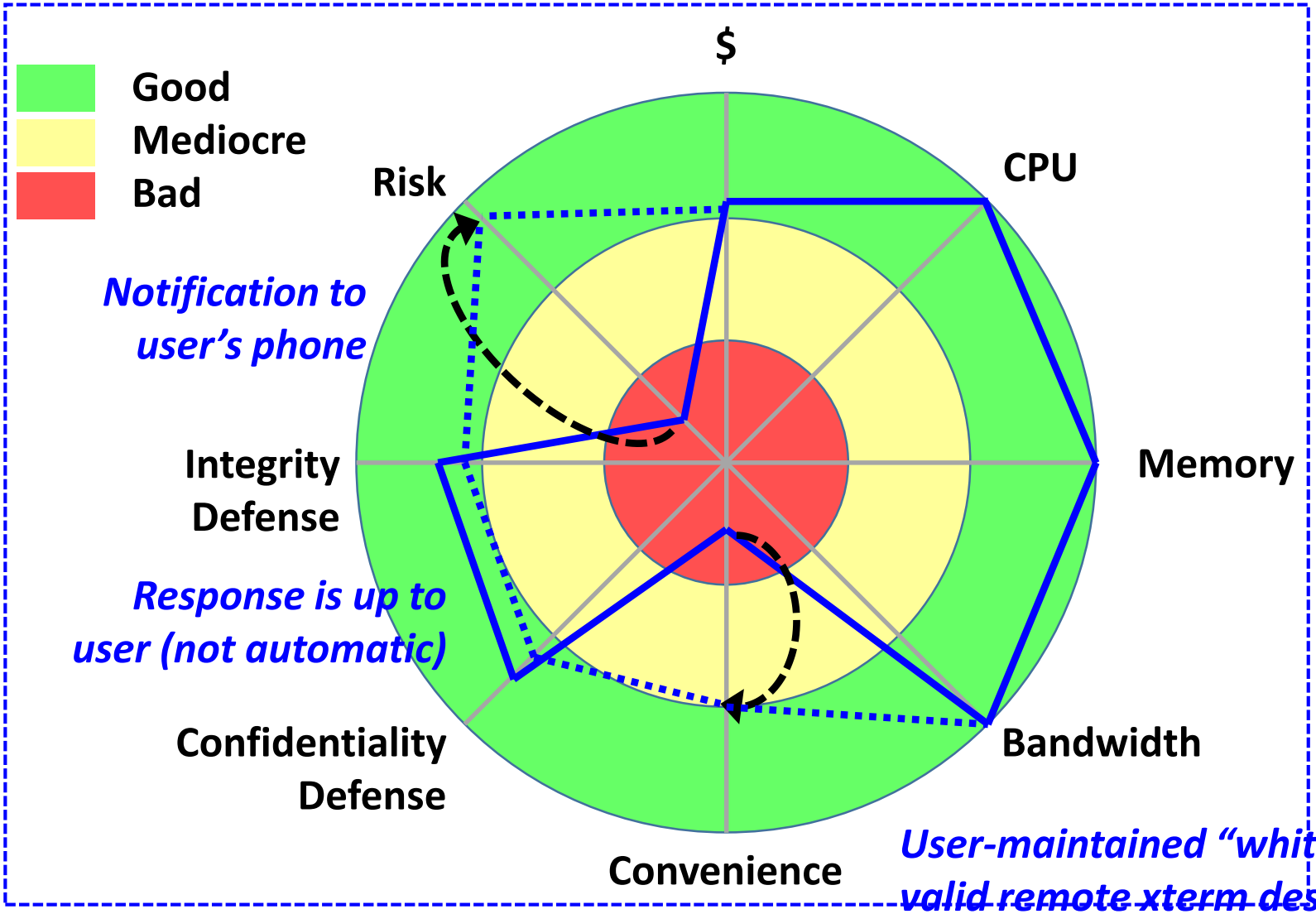


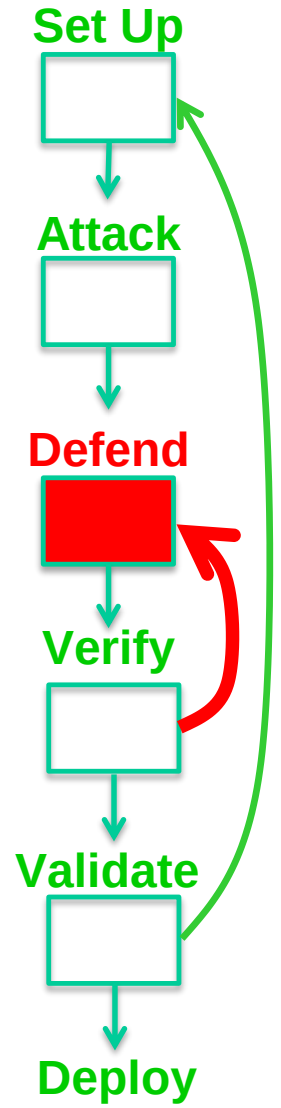
V&V workflow – *Redo* Defense





V&V workflow – *Redo* Defense





V&V workflow – Validate

CAUTIOUSLY deploy defense in operating environment

- Be willing to tolerate some disruption

IF SAFE TO DO SO, conduct attack

- Be prepared in case defense fails to stop attack

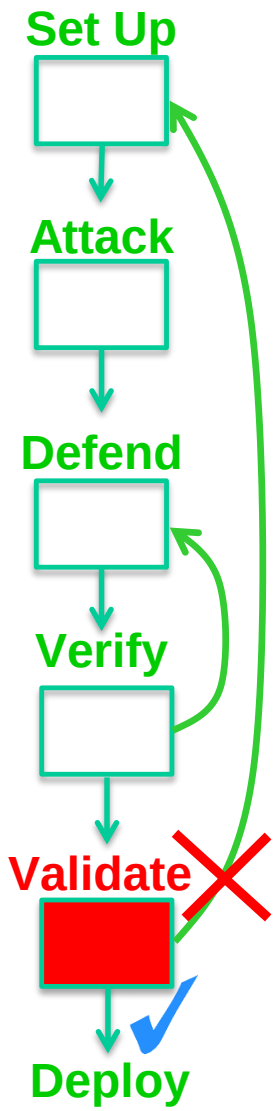
Is experience acceptable?

YES: advance to Deploy

NO: analyze what was wrong:

- Redesign defense
- Improve extrapolation
- Correct Set Up

"It is difficult to make predictions, especially about the future"



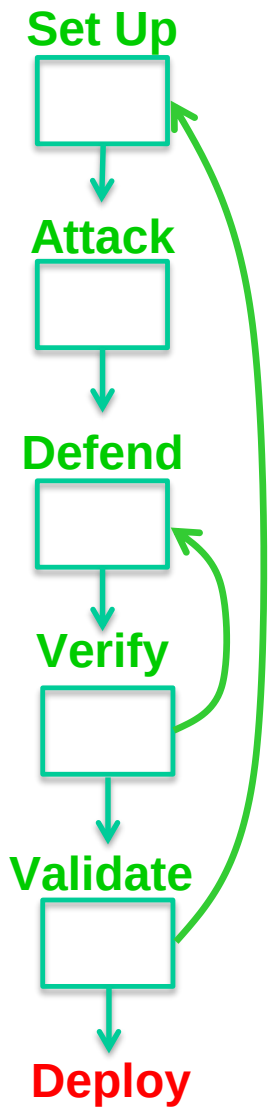
http://www.publicdomainpictures.net/view-image.php?image=10985

V&V workflow – Deploy

- Probationary period
  - Continue to maintain backup and fallback capabilities

- Limited extent
  - Subset of user community (learn from their experiences)
  - Subset of network

- Continue monitoring after full deployment
  - Internal and/or external conditions may change

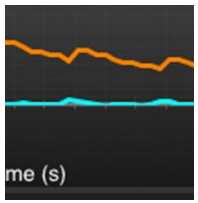


Guinea pigs: **Attribution:** Mikerussell at en.wikipedia

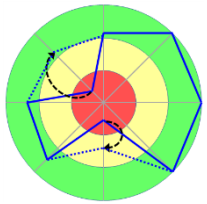
Recap

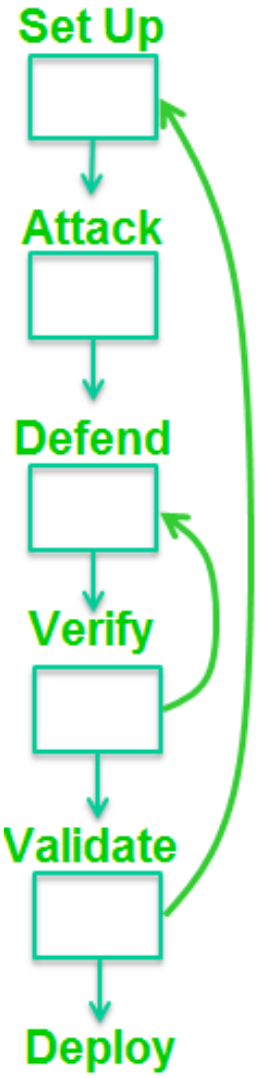
- Purpose: inform the deployment decision for a cyber defense
- JPL's Cyber Defense Research Laboratory – sandboxed environment for safely running security experiments
- Cyber defense concerns: costs, benefits, risks

- Fidelity challenge: cannot "test like you fly, fly like you test"
- V&V workflow: **Set Up → Attack → Defend → Verify → Validate → Deploy**
- Information visualization to comprehend & communicate



- Assessment and comparison of defense alternatives





Confounders & Pitfalls

- “Reconnaissance attack” defenses tested in a vastly simplified sandbox (no TFA, etc.)
- Used “as is” a detection query crafted only for demonstration – got some detection “escapes”

Future Work

- Continue to deploy – well-established operational environments vs. future ones
- Expand range of attacks & defenses
- Library of resource monitors and of artificial load

http://commons.wikimedia.org/wiki/File:HAL9000.svg

Global issues

Test lab environment and procedures:

- Test environment configuration
- Protocols for keeping testing safe
- Handling sensitive data about attacks and defenses

THANKS to our colleagues for their ongoing work on these in development of a Cyber Defense Research Laboratory

Assessment in a specific operational setting of:

- Cyber risk
- Mitigation from cyber defenses

An ongoing concern for us and the cyber community at large